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Shortcomings of cuffed paediatric tracheal tubes[†]

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Background. The goal of this investigation was to evaluate adequacy of the design of readily available paediatric cuffed tracheal tubes (CPTT).

Methods. In 15 series of cuffed (11) and uncuffed (four) paediatric tracheal tubes (ID: 2.5–7.0 mm) from four different manufacturers the following dimensions were measured: outer diameter of the tube, position and largest diameter of the tube cuff inflated at 20 cm H₂O and position of depth markings and compared with age-related dimensions.

Results. Outer diameters for tubes with similar IDs varied markedly between manufacturers and between cuffed and uncuffed tracheal tubes from the same manufacturer. Cuff diameters at 20 cm H₂O cuff pressure and cross-sectional cuff area at 20 cm H₂O cuff pressure did not always cover maximal internal age-related tracheal diameters and cross-sectional areas. Placing the tube tip in the mid-trachea, the cuffs of cuffed tubes with ID 3.0, 4.0, or 5.0 mm would become positioned within the larynx. If the cuffs were placed 1 cm below the cricoid level, many of the tube tips would be dangerously deep within the trachea. Only five of the 11 cuffed tubes had a depth marking. In many of these tubes the distances from depth marking to tube tip were greater than the age-related minimal tracheal length.

Conclusion. Most cuffed paediatric tracheal tubes are poorly designed, in particular the smaller sizes. A better design of cuffed tubes with a short high-volume, low-pressure cuff, cuff-free subglottic space and adequately placed depth markings are urgently needed.

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Until recently, cuffed tracheal tubes were recommended only for use with specific circumstances in children below 8–10 yr (low lung compliance, constant PCO_2 required, pulmonary function testing).^{1,2} In the last decade, several authors suggested the use of cuffed tracheal tubes in children younger than 8 yr.^{3–5} The advantages are less gas leak around the tracheal tube, with improved efficiency of ventilation, reduced atmospheric pollution, more reliable end-tidal carbon dioxide monitoring, lung function and oxygen consumption testing, and possibly low flow anaesthesia.^{6–9} Further benefits could be decreased risk of aspiration, reduced need to change ill-fitting tracheal tubes and less use of over-large uncuffed tubes, a main cause of subglottic stenosis.^{4,10–14}

However, there were concerns that cuff hyperinflation could cause tracheal mucosal injury (oedema, ulcerations, circular necrosis of the subglottic region) with the risk of complications such as stridor after extubation or subglottic

stenosis.^{15,16} The cuff will also reduce the internal diameter available for the tracheal tube and if tubes with a smaller internal diameter must be used, higher airway resistance, increased work of breathing, and difficult tracheo-bronchial suctioning may result.¹⁷

The design of cuffed paediatric tracheal tubes, in particular the position and size of the cuff and depth markings is an underestimated issue.¹⁶ Data that are available to compare the design of cuffed tracheal tubes for neonates, infants and children in relation to age-related anatomic data are limited.¹⁸

[†]*Declaration of interest.* The investigated paediatric cuffed tracheal tubes were ordered from local distributors and partially provided without charges. No financial support was obtained for the presented work. Dr Weiss and Dr Gerber are actually involved in designing a new cuffed paediatric tracheal tube in co-operation with Microcuff GmbH, Weinheim, Germany.

Table 1 Cuffed and uncuffed paediatric tracheal tubes included into the study (ID: internal diameter)

Manufacturer	No	Tracheal tube name	Reference number	Cuff
Sheridan, Hudson Respiratory Care, INC, Temecula, CA, USA	1	PED-SOFT—Uncuffed Tracheal Tube	5-30405 (ID 2.5)–5-30414 (ID 7.0)	–
	2	Murphy Eye, Oral/Nasal CF Cuffed Tracheal Tube Magill Type, Oral/Nasal	5-10206 (ID 3.0)–5-10214 (ID 7.0)	+
	3	CF Cuffed Tracheal Tube Murphy Eye, Oral/Nasal	5-10106 (ID 3.0)–5-10114 (ID 7.0)	+
Mallinckrodt Medical, Athlone, Ireland	4	Contour™ Tracheal Tube, Murphy Eye, Oral/Nasal	111-30 (ID 3.0)–111-70 (ID 7.0)	–
	5	Hi-Contour™ Tracheal Tube Murphy Eye, Oral/Nasal	107-30 (ID 3.0)–107-70 (ID 7.0)	+
	6	Hi-Contour™-Tracheal Tube Murphy Eye, Oral/Nasal (P-Serie)	P 107-30 (ID 3.0)–P 107-70 (ID 7.0)	+
	7	Lo-Contour™ Murphy Tracheal Tube, Oral/Nasal	301-30 (ID 3.0)–301-70 (ID 7.0)	+
	8	Lo-Contour™ Magill Tracheal Tube, Oral/Nasal	300-30 (ID 3.0)–300-70 (ID 7.0)	+
	9	Hi-Lo™ Tracheal Tube, Murphy, Oral/Nasal	109-50 (ID 5.0)–109-70 (ID 7.0)	+
	10	Safety-Flex™ Reinforced Tracheal Tube, Oral/Nasal	118-30 (ID 3.0)–118-70 (ID 7.0)	+
SIMS Portex Ltd, Hythe, Kent, UK	11	Tracheal Tube, Blue Line, Magill, oral/nasal, uncuffed	100/111/025 (ID 2.5)–100/111/070 (ID 7.0)	–
	12	Tracheal Tube—Profile Soft Seal Cuff, Murphy, oral/nasal	100/199/050 (ID 5.0)–100/199/070 (ID 7.0)	+
Rüsch GmbH, Kernen, Germany	13	Rüschelit® Safety Clear, Magill, nasal/oral	100380 (ID 2.5–ID 7.0)	–
	14	Rüschelit® Super Safety Clear, Murphy, nasal/oral	112482 (ID 2.5–ID 7.0)	+
	15	Rüschelit® Super Safety Clear, Magill, nasal/oral	112480 (ID 5.0–ID 7.0)	+

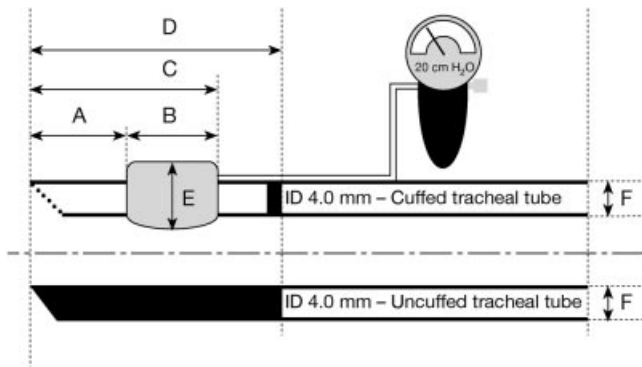


Fig 1 Diagram of measurements of uncuffed and cuffed paediatric tracheal tubes: A=distance between the distal tube tip and lower border of the tracheal cuff; B=length of the tracheal cuff; C=distance between the distal tube tip and upper border of the tracheal cuff; D=distance between the distal tube tip and upper border of the first depth marking if available; E=maximal diameter of the inflated cuff; F=outer diameter (OD) of the tube shaft measured above the tube cuff. All measures were taken with the cuff inflated to a pressure of 20 cm H₂O (ID=internal diameter).

Our goal was to evaluate the design of paediatric cuffed tracheal tubes (CPTT) from different manufacturers and to relate them to anatomical airway measures of the trachea from birth to adolescence.

Methods

In 2002, we ordered samples of paediatric cuffed (11) and uncuffed (four) tracheal tubes with ID from 2.5 to 7.0 mm as available made by four different manufacturers, from the local distributors (Table 1). We measured the following dimensions using a sliding calliper (Precision 1/10 mm): (A) distance from the distal tube tip to the lower border of the cuff; (B) length of the cuff; (C) distance from the distal tube tip to the upper border of the cuff; (D) distance between the distal tube tip to the upper border of the depth marking, if available; (E) maximal cross-sectional diameter of the inflated cuff; (F) outer diameter (OD) of the tube shaft above the cuff. All measurements were performed with the cuff inflated to a manometer pressure of 20 cm H₂O (Cuff Manometer, Mallinckrodt Medical, Athlone, Ireland) (Fig. 1).

Measurements were made in each brand by two investigators. Data are given with reference values provided by the manufacturer in parentheses, if available. The measurements were compared with age-related anatomical airway measures according to recommendations for the use of cuffed tracheal tubes in children from Khine and colleagues and Motoyama (Table 2).^{4,19}

Cuffed tube sizes are normally selected in accordance to the modified Cole's formula, which relates uncuffed tube size to age (i.e. ID (mm)=(age/4)+4.0).^{19,20} Essentially,

Table 2 Recommendations for appropriate size of uncuffed and cuffed paediatric tracheal tubes^{1 4 19 49}

Uncuffed paediatric tracheal tubes		Cuffed paediatric tracheal tubes			
Modified Cole's formula (ID=(age/4)+4.0) ^{19 21}		Motoyama formula (ID=(age/4)+3.5) ¹⁹		Khine formula (ID=(age/4)+3) ⁴	
Full-term neonate to 1st birthday	ID 3.5 mm uncuffed	Full-term neonate to 1st birthday	ID 3.0 mm cuffed	Full-term neonate to 1st birthday	ID 3.0 mm cuffed
1 yr to 2nd birthday	ID 4.0 mm uncuffed	1 yr to 2nd birthday	ID 3.5 mm cuffed	1 yr to 3rd birthday	ID 3.5 mm cuffed
2 yr to 4th birthday	ID 4.5 mm uncuffed	2 yr to 4th birthday	ID 4.0 mm cuffed	3 yr to 5th birthday	ID 4.0 mm cuffed
4 yr to 6th birthday	ID 5.0 mm uncuffed	4 yr to 6th birthday	ID 4.5 mm cuffed	5 yr to 7th birthday	ID 4.5 mm cuffed
6 yr to 8th birthday	ID 5.5 mm uncuffed	6 yr to 8th birthday	ID 5.0 mm cuffed	7 yr to 9th birthday	ID 5.0 mm cuffed
8 yr to 10th birthday	ID 6.0 mm uncuffed	8 yr to 10th birthday	ID 5.5 mm cuffed	9 yr to 11th birthday	ID 5.5 mm cuffed
10 yr to 12th birthday	ID 6.5 mm uncuffed	10 yr to 12th birthday	ID 6.0 mm cuffed	11 yr to 13th birthday	ID 6.0 mm cuffed
12 yr to 14th birthday	ID 7.0 mm uncuffed	12 yr to 14th birthday	ID 6.5 mm cuffed	13 yr to 15th birthday	ID 6.5 mm cuffed
14 yr to 16th birthday	ID 7.5 mm uncuffed	14 yr to 16th birthday	ID 7.0 mm cuffed	15 yr to 17th birthday	ID 7.0 mm cuffed

formulae for cuffed tracheal tube size reduce the ID of the tube by 0.5 or 1.0 mm to allow for the presence of the cuff (i.e. Motoyama, ID (mm)=(age/4)+3.5; Khine and colleagues, ID (mm)=(age/4)+3.0).^{4 19} In children under the age of 2 yr these equations are not applicable, and tube sizes have to be taken according to specific tables (Table 2).^{4 19 21}

Anatomical airway measures are calculated from the data of Pettersson and Ringertz to give the lower and/or upper normal limits (2 SD).²² The data were based on normal chest films obtained from 170 children and CT-examinations obtained from 130 children.^{23 24}

Results

We studied a total of 125 cuffed and uncuffed paediatric tracheal tubes (Table 1). In three series, cuffed tubes were only available from size ID 5.0 mm and greater. In one brand, only tubes of full size ID from 3.0 up to 6.0 mm were available from the manufacturer.

The outer diameters of the cuffed tubes varied markedly for a given ID, both between tubes from different manufacturers (0–0.9 mm) and between cuffed and uncuffed tracheal tubes from the same manufacturer (0–1.1 mm) (Table 3). In smaller tubes up to ID 4.5 mm, the outer diameters indicated by the manufacturer were the same or larger than the minimum age-related internal tracheal diameter for both the Khine and the Motoyama formula.

Cuff diameters and calculated cross-sectional cuff area at 20 cm H₂O cuff pressure did not always meet the age-related maximal internal tracheal diameter and/or cross-sectional area (Table 4). Only in some cuffed tubes of ID 5.0 mm and greater, did the cross-sectional cuff area become 150% of the internal tracheal cross-sectional area, corres-

ponding to the requirements of a high-volume/low-pressure (HVLP) tube cuff.

The upper border of the tracheal tube cuff corresponded in most series to the position of the depth marking of the next larger sized (+0.5 ID) uncuffed tracheal tube from the same manufacturer (Table 5). Therefore, if the tube tip were placed in the mid-trachea according to radiological criteria or the formula derived insertion depth, the cuffs of the ID 3.0, 4.0 or 5.0 mm tubes would lie in the subglottic larynx or even between the vocal cords or higher, particularly in tubes with Murphy eyes and long cuffs (Table 5 and Fig. 2).

Only five of 11 cuffed tube series had a depth marking (Table 5). These depth markings were positioned too high, with the distance from the tip of the tube being greater than the age-related minimal tracheal length. If the ID 3.0 mm cuffed tubes were inserted according to their depth marking, or with the upper border of the cuff below the lower border of the cricoid (1 cm below the vocal cords in neonates),²⁶ some of the tube tips would be dangerously low within the trachea (Fig. 3).

Discussion

Cuffed tracheal tubes have several benefits over uncuffed tracheal tubes. In adult patients requiring tracheal intubation these benefits are taken for granted and few anaesthetists would do without them. Cuffed tubes are not frequently used in European paediatric anaesthesia. For example, only 25% of paediatric anaesthetists in France use them routinely in 80% of their patients.^{5 27} Often the cuffs are either not inflated or only inflated if a large air leak is present. However, if cuffed tubes are to be used more and perhaps become routine, we need an adequately designed tube. Most

Table 3 Measured outer diameters (OD) of paediatric cuffed and uncuffed tracheal tubes and minimal (CI 95%) age-related internal tracheal diameters^{22 23} are provided for each tube ID according to the formula of Khine⁴ or the formula of Motoyama.¹⁹ Values in parentheses are measures provided by the manufactures. (NA: not available tubes=tubes not produced by the manufacturer)

ID	Tracheal tube brand	No	Cuff	2.5	3.0	3.5	4.0	4.5	5.0	5.5	6.0	6.5	7.0
Outer diameter (OD) (mm)	Sheridan Tracheal Tube uncuffed	1	–	3.6 (3.6)	4.3 (4.2)	4.9 (4.9)	5.5 (5.5)	6.2 (6.2)	6.8 (6.8)	7.5 (7.5)	8.2 (8.2)	8.8 (8.8)	9.6 (9.6)
	Murphy Sheridan Tracheal Tube cuffed	2	+	NA	4.2 (4.2)	4.9 (4.9)	5.5 (5.5)	6.2 (6.2)	6.8 (6.8)	7.5 (7.5)	8.2 (8.2)	8.8 (8.8)	9.6 (9.6)
	Murphy Sheridan Tracheal Tube cuffed	3	+	NA	4.3 (4.2)	NA	5.5 (5.5)	NA	6.9 (6.8)	NA	8.1 (8.2)	8.9 (8.8)	9.4 (9.6)
	Magill Mallinckrodt TT Contour	4	–	3.7 (3.6)	4.4 (4.3)	5.0 (4.9)	5.7 (5.6)	6.2 (6.2)	6.9 (6.9)	7.6 (7.5)	8.1 (8.2)	8.8 (8.8)	9.6 (9.6)
	Mallinckrodt TT High—Contour	5	+	NA	4.4 (4.3)	4.9 (4.8)	5.7 (5.6)	6.3 (6.2)	7.0 (6.9)	7.6 (7.5)	8.2 (8.2)	8.9 (8.8)	9.5 (9.6)
	Murphy Mallinckrodt TT High—Contour	6	+	NA	4.3 (4.3)	5.0 (4.9)	5.7 (5.6)	6.4 (6.2)	6.7 (6.9)	7.7 (7.5)	8.1 (8.2)	8.9 (8.8)	9.4 (9.6)
	Murphy P-Serie Mallinckrodt TT Lo—Contour	7	+	NA	4.5 (4.3)	4.9 (4.8)	5.7 (5.6)	6.2 (6.2)	6.9 (6.9)	7.5 (7.5)	8.3 (8.2)	9.0 (8.8)	9.8 (9.6)
	Magill Mallinckrodt TT Lo—Contour	8	+	NA	4.4 (4.3)	5.0 (4.8)	5.6 (5.6)	6.2 (6.2)	7.0 (6.9)	7.5 (7.5)	8.2 (8.2)	8.8 (8.8)	9.4 (9.6)
	Murphy Mallinckrodt TT Hi-Lo	9	+	NA	NA	NA	NA	NA	6.9 (6.9)	7.5 (7.5)	8.1 (8.2)	8.8 (8.8)	9.4 (9.6)
	Murphy Mallinckrodt TT Safety Flex	10	+	NA	5.2 (5.0)	5.5 (5.2)	6.2 (6.2)	6.7 (6.7)	7.2 (6.9)	7.9 (7.5)	8.5 (8.2)	9.2 (8.8)	9.8 (9.6)
	Portex TT—Blue Line, Magill, uncuffed	11	–	3.4 (3.4)	4.2 (4.2)	4.8 (4.8)	5.5 (5.4)	6.1 (6.2)	6.8 (6.9)	7.5 (7.6)	8.2 (8.2)	9.0 (8.9)	9.7 (9.6)
	Portex TT—Profile Soft Seal Cuff, Murphy	12	+	NA	NA	NA	NA	NA	7.0 (6.9)	7.6 (7.6)	8.3 (8.2)	8.8 (8.9)	9.6 (9.6)
	Rüsch Ruschelit Safety Clear	13	–	3.4 (3.3)	4.0 (4.0)	4.8 (4.7)	5.3 (5.3)	6.0 (6.0)	6.7 (6.7)	7.3 (7.3)	8.0 (8.0)	8.8 (8.7)	9.4 (9.3)
	Rüsch Ruschelit Super Safety Clear	14	+	4.0 (4.0)	5.1 (5.0)	5.3 (5.3)	5.9 (6.0)	6.2 (6.3)	6.7 (6.7)	7.2 (7.3)	8.0 (8.0)	8.7 (8.7)	9.0 (9.3)
	Rüsch Ruschelit Super Safety Clear	15	+	NA	NA	NA	NA	NA	6.7 (6.7)	7.3 (7.3)	8.0 (8.0)	8.8 (8.7)	9.2 (9.3)
	Murphy (mm)			2.5	3.0	3.5	4.0	4.5	5.0	5.5	6.0	6.5	7.0
	ID-related age ranges according to Khine ⁴			Premature neonate	Full-term neonate to 1st birthday	1 yr to 3rd birthday	3 yr to 5th birthday	5 yr to 7th birthday	7 yr to 9th birthday	9 yr to 11th birthday	11 yr to 13th birthday	13 yr to 15th birthday	15 yr to 16th birthday
	Minimal age-related internal tracheal diameter (mm) ^{22 23}				3.6	4.1	5.2	6.3	7.4	8.5	9.6	10.8	11.9
	ID-related age ranges according to Motoyama ¹⁹			Premature neonate	Full-term neonate to 1st birthday	1 yr to 2nd birthday	2 yr to 4th birthday	4 yr to 6th birthday	6 yr to 8th birthday	8 yr to 10th birthday	10 yr to 12th birthday	12 yr to 14th birthday	14 yr to 16th birthday
	Minimal age-related internal tracheal diameter (mm) ^{22 23}				3.6	4.1	4.7	5.8	6.9	8.0	9.1	10.2	11.3

commercially available CPTT have substantial problems with outer diameter, cuff position, cuff diameter and depth markings.

Outer diameters

Variation in tracheal tube wall thickness is related to the nature of the material (Latex, PCV), risk of kinking, presence of wire reinforcement, and variations as a result of manufacturing. This results in different outer diameters for tubes with identical internal tube diameter (Table 3). Most anaesthetists are probably not aware of differences in outer tube diameters because tracheal tubes are chosen according to the internal diameter. This leads to possible use of oversized, ill-fitting tubes so that the tube may need to be changed or there could be risk of subglottic damage. In addition, the effective outer tracheal tube diameter of cuffed tubes includes the deflated cuff which can be considerably larger than the OD printed on the tube shaft and varies with cuff type and manufacturer.^{28 29} Because outer tube diameters for a given internal diameter from different manufacturers varies by as much as 0.9 mm, it is not surprising that several formulas to predict proper tube size have been proposed for cuffed and uncuffed tubes in children.^{2 19 20 21 30–32}

Cuff diameters

Tracheal tube cuffs seal better if inflated to a higher pressure. To avoid high-cuff pressures, HVLP cuffs are now standard in adult use.³³ They are based on the principle that at 20 cm H₂O cuff pressure the cross-sectional area of the cuff corresponds to about 150% of the internal cross-sectional area of the trachea. Thus, HVLP cuffs seal the trachea by filling the internal tracheal lumen at low pressure. We found that none of the CPTT that we studied up to an ID of 4.5 mm met the requirements of a HVLP tube cuff, although some did in the larger sizes. In addition, many of the cuff diameters and cross-sectional areas were the same as or even smaller than age-related maximal dimensions (Table 4). Consequently, cuff pressures of more than 20 cm H₂O would be needed to seal the tracheal lumen. Although cuff pressures about 25–30 cm H₂O are accepted as the upper limit of safety for adults, no data exist in children about cuff pressure limits and lower cuff pressures are preferable.³⁴

Cuff position

In most of the cuffed tubes, the upper border of the cuff corresponds to the upper border of the depth marking of the next larger sized uncuffed tracheal tube. Thus, the cuff would lie in the subglottic space, between the vocal cords, or even in the supraglottic space if the tubes are placed either according to radiological criteria or to an age-related formula for predicting depth of tube insertion (Fig. 2).^{35 36}

This is probably why two manufacturers provide HVLP cuffs only from tube size ID 5.0 mm and higher (No. 9 and 12). Rüsch provides a cuffed tube with Murphy eye (No. 14) only from tube size ID 5.0 mm upwards, whereas the corresponding tube in the Magill version is provided from size ID 2.5 mm. The Sheridan Tracheal Tube Cuffed Magill (No. 3) seems to be least likely to allow a laryngeal cuff position. However, the use of this tube is limited by the availability of only integer values of ID up to ID 6.0 mm, which reduces the chance of an adequate seal, because the tubes are used over an age range of 4 yr.

Excessive subglottic pressure can cause mucosal ischaemia, fibrosis, and lead to stenosis, by compression of the mucosa against the non-expandable cricoid cartilage. For the same reason, the cuff must not be intra-laryngeal. In addition, sharp folds and edges of the cuff membrane, particularly if the cuff is deliberately deflated, can damage the airway by cutting the mucosa when the tube moves during the respiratory cycle. This leads to granulation tissue formation, fibrosis, and intra-laryngeal web formation around the tracheal tube.³⁷ The cuff should be located below the cricoid ring, at the level of the tracheal rings, which are able to expand. Secondly, a tracheal tube cuff within the larynx can cause vocal cord palsy, perhaps by compression of the recurrent laryngeal nerve between the cuff and the thyroid lamina.³⁸

If the cuff of the tube is placed below the cricoid or if external cuff palpation is used to locate the tube,³⁹ then some tube tips will be too far down the trachea, particularly in tubes with a Murphy eye and a long cuff (Fig. 3). The reduced margin of safety of cuffed paediatric tracheal tubes even with the cuff placed within the larynx has been noted by Ho and colleagues¹³ and is a serious problem with current cuffed tubes. Endobronchial intubation can occur with head-neck flexion or cranial migration of the carina in laparoscopic surgery or the Trendelenburg position.^{40–44}

Depth markings

Depth markings on CPTT are essential to allow a cuff-free distance below the vocal cords to the cricoid level for the above reasons and to avoid over-insertion.^{45–47} Only five of 11 of the cuffed tubes that we investigated had a depth marking (Fig. 2). As the upper border of the depth marking is placed at the level of the vocal cords, almost all of these depth markings were too high up the tube shaft and corresponded to the minimal tracheal length for that age-group (Table 5 and Fig. 3). Generally, appropriate placement of cuffed tubes in the trachea and safety during head flexion will need shorter cuffs and adequate depth markings to guarantee a cuff position below the cricoid and a tip far enough above the tracheal carina. The length of the cuff and the presence of a Murphy eye are important determinants of final cuff position in CPTT. Thus short tube cuffs should be used and a Murphy eye must be avoided to allow placing the tube cuff more distally on the tube shaft.

Table 4 Measured cuff diameters and calculated cross-sectional areas (manufacturer data) at 20 cm H₂O cuff pressure are provided with upper 95% limit of age-related internal tracheal diameters and cross-sectional tracheal areas^{22–24} for each tube ID according to the formula of Khine⁴ or to the formula of Motoyama.¹⁹ Values in parentheses are measures provided by the manufacturers. (NA: not available tubes=tubes not produced by the manufacturer)

ID	Tracheal tube brand	No	Cuff	2.5	3.0	3.5	4.0	4.5	5.0	5.5	6.0	6.5	7.0
Cuff diameter (mm) at 20 cm H ₂ O cuff pressure	Sheridan Tracheal Tube cuffed Murphy	2	+	NA	7.0 (7.3)	8.8 (8.9)	8.8 (8.9)	11 (11)	13 (13)	16 (16)	16 (16)	19 (19)	19 (19)
	Sheridan Tracheal Tube cuffed Magill	3	+	NA	7.1 (7.3)	NA	8.5 (8.9)	NA	13 (13)	NA	16 (16)	18 (19)	18 (19)
	Mallinckrodt TT High—Contour Murphy	5	+	NA	6 (6)	7 (7)	8 (8)	11 (11)	20 (18)	21 (21)	23 (22)	24 (23)	28 (25)
	Mallinckrodt TT High—Contour Murphy P-Serie	6	+	NA	6.5 (6)	7 (7)	8 (8)	12 (11)	20 (18)	22 (21)	23 (22)	24 (23)	28 (25)
	Mallinckrodt TT Lo—Contour Magill	7	+	NA	6 (6)	7 (7)	8 (8)	11 (11)	17 (17)	19 (19)	21 (21)	22 (22)	24 (24)
	Mallinckrodt TT Lo—Contour Murphy	8	+	NA	6 (6)	7 (7)	8 (8)	11 (11)	17 (17)	19 (19)	21 (21)	22 (22)	24 (24)
	Mallinckrodt TT Hi-Lo Murphy	9	+	NA	NA	NA	NA	NA	20.5 (20)	21 (21)	23 (23)	25 (25)	28 (28)
	Mallinckrodt TT Safety Flex	10	+	NA	7 (6)	8 (7)	9 (8)	11 (11)	17 (17)	19 (19)	21 (21)	22 (22)	24 (24)
	Portex TT—Profile Soft Seal Cuff, Murphy	12	+	NA	NA	NA	NA	NA	16 (17)	17 (17)	23 (23)	23 (23)	30 (30)
	Rüsch Rüschelit Super Safety Clear Magill	14	+	8 (8)	8 (8)	8 (8)	10 (10.5)	10 (10.5)	12 (13)	14.5 (16.5)	16.5 (18.5)	18.5 (20.5)	24 (24)
	Rüsch Rüschelit Super Safety Clear Murphy	15	+	NA	NA	NA	NA	NA	11 (13)	16.5 (16.5)	16 (18.5)	20.5 (20.5)	23 (24)
	Sheridan Tracheal Tube cuffed Murphy	2	+	NA	42	62	62	95	133	201	201	283	283
	Sheridan Tracheal Tube cuffed Magill	3	+	NA	42	NA	62	NA	133	NA	201	283	283
	Mallinckrodt TT High—Contour Murphy	5	+	NA	28	38	50	95	254	346	380	415	491
	Mallinckrodt TT High—Contour Murphy P-Serie	6	+	NA	28	38	50	95	254	346	380	415	491
Cross-sectional cuff area (mm ²) at 20 cm H ₂ O cuff pressure													

Table 4 *Continued*

ID	Tracheal tube brand	No	Cuff	2.5	3.0	3.5	4.0	4.5	5.0	5.5	6.0	6.5	7.0
ID Tracheal diameters	Mallinckrodt TT Lo—Contour Magill	7	+	NA	28	38	50	95	227	283	346	380	452
	Mallinckrodt TT Lo—Contour Murphy	8	+	NA	28	38	50	95	227	283	346	380	452
	Mallinckrodt TT Hi-Lo Murphy	9	+	NA	NA	NA	NA	NA	314	346	415	490	615
	Mallinckrodt TT Safety Flex	10	+	NA	28	38	50	95	227	283	346	380	452
	Portex TT—Profile Soft Seal Cuff, Murphy	12	+	NA	NA	NA	NA	NA	201	227	415	415	707
	Rüsch Rüschelit Super Safety Clear Magill	14	+	50	50	50	87	87	133	214	269	330	452
	Rüsch Rüschelit Super Safety Clear Murphy	15	+	NA	NA	NA	NA	NA	133	214	269	330	452
	(mm)												
	ID-related age ranges according to Khine ⁴			2.5 Premature neonate	3.0 Full-term neonate to 1st birthday	3.5 1 yr to 3rd birthday	4.0 3 yr to 5th birthday	4.5 5 yr to 7th birthday	5.0 7 yr to 9th birthday	5.5 9 yr to 11th birthday	6.0 11 yr to 13th birthday	6.5 13 yr to 15th birthday	7.0 15 yr to 16th birthday
	Maximal age-related internal tracheal diameter (mm) ^{22 23}				8.3	9.5	10.6	11.7	12.8	13.9	15.0	16.3	17.3 ²⁴
	Maximal age-related cross-sectional tracheal area (mm ²) ^{20 23}				35.3	58.4	81.5	104.7	127.8	151.0	174.1	197.2	234.9
	ID-related age ranges according to Motoyama ¹⁹			Premature neonate	Full-term neonate to 1st birthday	1 yr to 2nd birthday	2 yr to 4th birthday	4 yr to 6th birthday	6 yr to 8th birthday	8 yr to 10th birthday	10 yr to 12th birthday	12 yr to 14th birthday	14 yr to 16th birthday
	Maximal age-related internal tracheal diameter (mm) ^{22 23}				8.3	8.9	10.0	11.1	12.2	13.3	14.4	15.7	17.3 ²⁴
	Maximal age-related cross-sectional tracheal area (mm ²) ^{22 23}				35.3	46.8	70.0	93.1	116.2	139.4	162.5	185.7	234.9

Formulae for selection of cuffed paediatric tracheal tubes

A satisfactory cuffed tube size in children depends on the size of outer tube and cuff diameter so that an air leak around the tube at 20 cm H₂O can be established with the cuff not inflated (fit) and no air leakage occurs at a cuff pressure of 20 cm H₂O (seal). The two age-related predictors of size for cuffed tracheal tubes in children

older than 2 yr are limited both generally and specifically for different tube brands. Using the Motoyama formula¹⁹ (ID=[age/4]+3.5) will give an adequate seal more often but more tubes will be too large (according to Table 2). On the other hand using the Khine-formula⁴ (ID=[age/4]+ 3) fewer tubes will be too large but many will not adequately seal the trachea (Tables 3 and 4). Such facts may reflect the inadequacies of the formulae for appropriate tube choice as much as poor design. However, as indicated by Tables 3 and

Table 5 Measured cuff-related distances (distance from tube tip to lower and upper border of the cuff (A/C; Fig. 1) and distance from tube tip to upper border of the depth marking (D) if available. Age-related tracheal lengths^{22 23 25} are provided for each tube ID according to the formula of Khine⁴ or to the formula of Motoyama.¹⁹ Tracheal length is measured from vocal cords to carina. (NA: not available tubes=tubes not produced by the manufacturer)

ID	(mm)	No	Cuff	2.5	3.0	3.5	4.0	4.5	5.0	5.5	6.0	6.5	7.0
Distances A/C/D (mm)	Sheridan Tracheal Tube uncuffed	1		–/–/21	–/–/22	–/–/24	–/–/27	–/–/29	–/–/31	–/–/31	–/–/35	–/–/37	–/–/41
	Murphy Sheridan Tracheal Tube cuffed	2	+	NA	12/25/–	13/32/–	13/32/–	15/35/–	20/42/–	20/46/–	21/48/–	23/55/–	25/60/–
	Murphy Sheridan Tracheal Tube cuffed	3	+	NA	10/23/–	NA	10/27/–	NA	12/35/–	NA	14/40/–	14/47/–	16/50/–
	Magill Mallinckrodt TT Contour	4		–/–/30	–/–/30	–/–/30	–/–/30	–/–/30	–/–/29	–/–/30	–/–/29	–/–/31	–/–/31
	Magill Mallinckrodt TT High—Contour	5	+	NA	14/26/–	13/26/–	16/30/–	19/37/–	20/40/–	20/44/–	21/51/–	21/49/–	26/54/–
	Murphy Mallinckrodt TT High—Contour	6	+	NA	13/24/42	16/29/50	17/30/49	22/39/57	20/37/59	22/43/62	18/40/60	24/49/67	19/46/67
	Murphy P-Serie Mallinckrodt TT Lo—Contour	7	+	NA	11/21/–	11/23/–	12/27/–	12/29/–	12/43/–	17/50/–	17/50/–	17/50/–	19/60/–
	Magill Mallinckrodt TT Lo—Contour	8	+	NA	14/24/–	16/27/–	15/29/–	18/36/–	19/49/–	21/53/–	21/54/–	24/57/–	26/66/–
	Murphy Mallinckrodt TT Hi-Lo	9	+	NA	NA	NA	NA	NA	19/46/–	19/47/–	18/48/–	19/51/–	20/53/–
	Murphy Mallinckrodt TT Safety	10	+	NA	10/21/42	11/26/44	11/26/47	12/30/53	17/45/68	15/50/70	18/50/70	18/52/72	18/56/80
	Flex Portex TT—Blue Line, Magill, uncuffed	11	–	–/–/22	–/–/27	–/–/32	–/–/37	–/–/42	–/–/47	–/–/52	–/–/59	–/–/–	–/–/–
	Portex TT—Profile Soft Seal Cuff, Murphy	12	+	NA	NA	NA	NA	NA	20/42/76	21/45/79	23/53/84	22/51/85	24/58/92
	Rüsch Rüschelit Safety Clear	13	–	–/–/20	–/–/20	–/–/21	–/–/30	–/–/30	–/–/40	–/–/39	–/–/40	–/–/41	–/–/–
	Rüsch Rüschelit Super Safety Clear Magill	14	+	9/21/36	12/28/40	11/30/44	14/33/47	13/32/48	17/42/70	16/42/70	16/48/79	18/52/80	18/54/84
	Rüsch Rüschelit Super Safety Clear Murphy	15	+	NA	NA	NA	NA	NA	21/47/76	20/47/76	22/55/82	23/57/84	25/63/88
ID Tracheal length	(mm) ID-related age ranges according to Khine ⁴			2.5 Premature neonate	3.0 Full-term neonate	3.5 1 yr	4.0 3 yr	4.5 5 yr	5.0 7 yr	5.5 9 yr	6.0 11 yr	6.5 13 yr	7.0 15 yr

Table 5 Continued

ID	(mm)	No	Cuff	2.5	3.0	3.5	4.0	4.5	5.0	5.5	6.0	6.5	7.0
Tracheal length	Age-related 95 % range of tracheal length (mm) ^{22 23}				39.4–60.5	43.0–65.8	50.2–76.4	57.4–87.1	64.6–97.7	71.8–108.3	78.9–119	86.1–129.6	93.3–140.2
	Tracheal length (mm) ²⁵				40	45	53	56	59	61	–	–	–
	ID-related age ranges according to Motoyama ¹⁹			Premature neonate	Full-term neonate	1 yr	2 yr	4 yr	6 yr	8 yr	10 yr	12 yr	14 yr
	Age-related 95% range of tracheal length (mm) ^{22 23}				39.4–60.5	43.0–65.8	46.6–71.1	53.8–81.8	61.0–92.4	68.2–103.0	75.4–113.7	82.5–124.3	89.7–134.9
	Tracheal length (mm) ²⁵				40	45	50	54	57	60	63	–	–
	Tracheal length (mm) ²⁵												

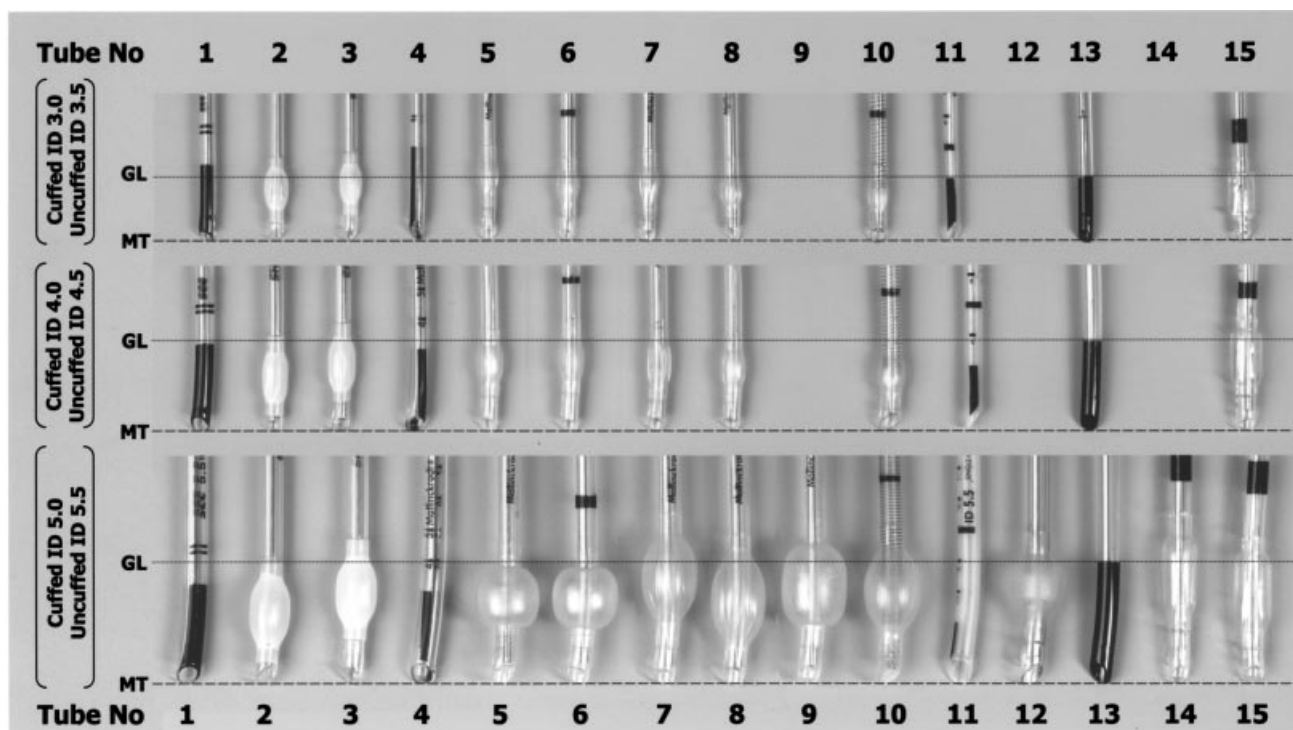


Fig 2 ID 3.0, 4.0, and 5.0 mm cuffed tracheal tubes and age-related corresponding (ID+0.5 mm) uncuffed tracheal tubes are shown for each of the 15 tube brands. Age-related mid-trachea (MT) placement of the tube tip according to the depth marking of the uncuffed tracheal tube results in laryngeal or even glottic level (GL) position of the cuff for all the cuffed tracheal tubes.

4, using a larger tube gives a better seal but less fit and inadequate long cuffs, and a smaller tube would result in a better fit but worse seal. Thus, rather than trying to change these formulae, the tubes should be adapted to meet expected anatomical data and the manufacturer should indicate for the appropriate age group for a specific sized tracheal tube.

Table 3 shows that in small children even with the Khine formula, using a cuffed tube 1 mm smaller than an uncuffed tube, there remains a risk that the tube will be too large for the trachea. The internal diameter of the cricoid is even

slightly smaller than the trachea in children below 8–10 yr. However, further reduction of ID below the size than recommended by Khine is not suitable, because it further increases tube resistance, makes IPPV more necessary and restricts suctioning. In addition, cuffed tubes with an ID 2 and 2.5 mm are not widely available, if at all. Thus, in very small children (<3 kg) uncuffed tubes are still required.

We did not assess all commercially available cuffed and uncuffed paediatric tracheal tubes nor did we study special preformed tubes such as oral or nasal RAE tubes. However, we studied a representative set of widely used paediatric

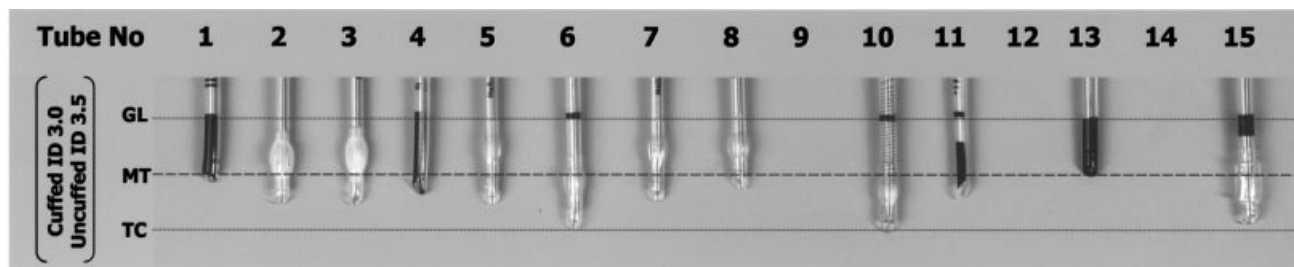


Fig 3 ID 3.0 mm cuffed tracheal tubes and age-related corresponding ID 3.5 mm uncuffed tracheal tubes are shown in 12 available tube brands. Missing CPTT are tracheal tubes not manufactured (Table 1). With the depth marking positioned at the glottic level (GL) or with the upper border of the cuff positioned 1 cm below the vocal cords some of the CPTT become with their tube tip critically low in the trachea (MT=mid-trachea; TC=tracheal carina).

tubes. Good cuff position in preformed oral and nasal tracheal tubes is of particular interest but this can only be assessed *in vivo*. We did not compare our measurements with the dimensions claimed by the manufacturers, nor variations between different lots, although within one brand, dimensions can vary considerably between production lots and manufacturing sites.

We found differences in outer tube diameters of current commercially available cuffed paediatric tracheal tubes. The position and size of the tracheal tube cuff, and the absence of an adequate depth marking are major limitations for correct tracheal tube placement. Ideally, a cuffed paediatric tracheal tube should have a HVLP with a short cuff length, adequate depth markings and not allow the cuff to be inflated in the subglottic region.

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